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A review of different heat exchangers designs for increasing the diesel exhaust waste heat recovery

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ABSTRACT

In this paper, after a short review of waste heat recovery technologies from diesel engines, the heat exchangers (HEXs) used in exhaust of engines is introduced as the most common way. So, a short review of the technologies that increase the heat transfer in HEXs is introduced and the availability of using them in the exhaust of engines is evaluated and finally a complete review of different HEXs which previously were designed for increasing the exhaust waste heat recovery is presented. Also, future view points for next HEXs designs are proposed to increase heat recovery from the exhaust of diesel engines.

Contents

Abbreviations: BSFC, brake specific fuel consumption; LHA, latent heat accumulator; CCHP, combined cooling, heating and power; LMTD, log mean temperature difference; CFD, computational fluid dynamic; MEP, mean effective pressure; CHP, combined heating and power; MHD, magneto-hydrodynamic; CI, compression ignition; ORC, Organic Rankine Cycle; DI, direct injection; PCM, phase change materials; DOE, design of experiment; RNG, renormalization-group; EGR, exhaust gas recirculation; SST, Shear-Stress Transport; EHD, electro-hydrodynamic; SI, spark ignition; FDM, finite difference method; TEG, thermoelectric generator; GHG, greenhouse gases; VGT, variable geometry turbines; HEX, heat exchanger; WHR, waste heat recovery

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Nomenclature

C_p	specific heat at constant pressure (kJ/kg K)
e	specific exergy (kJ/kg)
g	gravity acceleration (m^2/s)
h	specific enthalpy (kJ/kg)
$\dot{m}$	mass flow rate (kg/s)
M	molecular weight of exhaust gas (kg/mol)
p	pressure (bar)
P_b	brake power (kW)
$\dot{Q}$	heat flux (W)
$\overline{R}$	universal gas constant (kJ/mol K)
s	absolute entropy of ideal gas (kJ/kg K)
T	temperature (°C)
u,v,w	velocity components (m/s)
U	overall heat transfer coefficient (W/m K)

Greeks

ε	heat exchanger effectiveness
ρ	density (kg/m^3)
τ	shear stress (N/m^2)
η	second law heat exchanger efficiency
ν	specific volume (m^3/kg)

1. Introduction

Nowadays, diesel engines are widely used due to their abilities and advantages in industries for producing energy, electricity, transportation, etc., but a large amount of their fuel energy is wasted through the exhaust [1]. Researchers confirm that more than 30–40% of fuel energy gets wasted from the exhaust and just 12–25% of the fuel energy converts to useful work [2,3]. On the other hand, statistics show that the production of a large number of internal combustion engines increases the presence of harmful greenhouse gases (GHG) which is a cause of concern. So, researchers are motivated to recover the heat from the waste sources in engines by using applicable ways. Heat recovery not only reduces the demand of fossil fuels, but also reduces the GHG and helps to save energy. Rakopoulos [4] mentioned that one of the main aims of the second law of thermodynamic, in engines, is identifying the source of destruction and suggesting ways to convert these destructions to useful work or to use them. Combustion is one of the main sources of energy destruction in engines which many researchers aimed to reduce its irreversibility property. For example, Li et al. [5] investigated the effect of swirl chamber on combustion irreversibilities and concluded that increasing the chamber volume increases the irreversibilities due to lower temperature and pressure in the cylinder. Ghazikhani et al. [6] investigated the exhaust gas recirculation (EGR) effect and mentioned that EGR cannot improve the combustion process from the second law view point. Primus et al. [7] tried to reduce the irreversibilities by insulating the cylinder. They observed a 3.7% increase in the indicated work and 49% increase in exergy of exhaust gases, but their study showed that NOx also increases which is not appropriate. Many studies are done on using the alternative fuels to improve the combustion process. Approximately all of them reveal that hydrogen enrichment can improve the combustion process [8–10]. Alasfour [11] showed that 30% Butanol added to gasoline makes a 7% reduction in the second law efficiency and was not appropriate from the second law view point, while Rakopoulos and Kyritsis [12] reduced the combustion irreversibilities by using methane and methanol. Also, Ghazikhani et al. [13] confirmed that just 5% ethanol can improve the combustion process through the second law view point in an experimental work.

It is evident that exhaust of the engines is another main source from which a large amount of energy gets wasted through it. This energy can be recovered by using the heat exchanger in exhaust and this recovered heat is then used in the cycles such as Organic Rankine Cycle (ORC), combined heating and power (CHP), combined cooling, heating and power (CCHP), etc. In all these applications, requirement of a heat exchanger is necessary to transmit the heat from hot gases to working fluid at excellent efficiency. On the other hand, since exhaust heat exchanger may cause a pressure drop and affects the engine performance, its design is of great importance. The current paper aims to introduce the ways to recover heat from engines. Also, a review of previous heat exchangers designs is performed and suggestions for future developments are presented.

2. Waste heat recovery technologies in engines

In this section, a short review of the technologies for heat transfer from engines is presented. In the current status of the world the requirement of energy is increasing especially for transportation applications, so the usage of fossil fuels and consequently harmful greenhouse gases (GHG) will increase. Researchers attempt to reduce the need of fossils fuels by using the waste heat recovery from engines. As of now, six technologies are presented for engines waste heat recovery of which Saidur et al. [14] have performed a complete review of four of them. These six technologies are thermoelectric generators (TEG), Organic Rankine Cycle (ORC), six stroke engines, turbocharging, exhaust gas recirculation (EGR) andexhaust heat exchangers (HEXs)and a short introduction to each of them is given below.

2.1. Thermoelectric generators

Thermoelectric generators (TEG) or Seebeck generators are devices which directly convert waste heat energy into electrical energy. These devices work on Seebeck effect which was discovered by Thomas Johann Seebeck in 1821 [15]. Recently, for increasing the efficiency of these devices, semiconductor p–n junctions were added (Fig. 1)that are made up of new materials such as BiTe (bismuth telluride), CeFeSb (skutterudite), ZnBe (zinc–beryllium), SiGe (silicon–germanium), SnTe (tin telluride) and new nano-crystalline or nano-wire thermoelectric which increase their efficiency to around 5–8% [14]. Although TEG devices have many advantages such as clean energy, without sound, without movable component and lesser maintenance costs, they are however only economical when used at high temperatures (> 200 °C) and when only small amounts of the power (a few milliwatts) are needed. TEG's advantages motivated many of the researchers to use it in automobile waste heat recoveries which can be seen in [14]. For instance, Karri et al. [16] studied two cases of exhaust waste heat recovery using TEGs. Also, Zhang and Chau [17] reported that using TEG has low effect on engine performance and it can improve the engine power up to 17.9%. But, in another research, Yu and Chau [18] revealed that when the exhaust gases flow through the TEG's heat exchanger, kinetic energy from the gases is lost and causes an increase in pumping

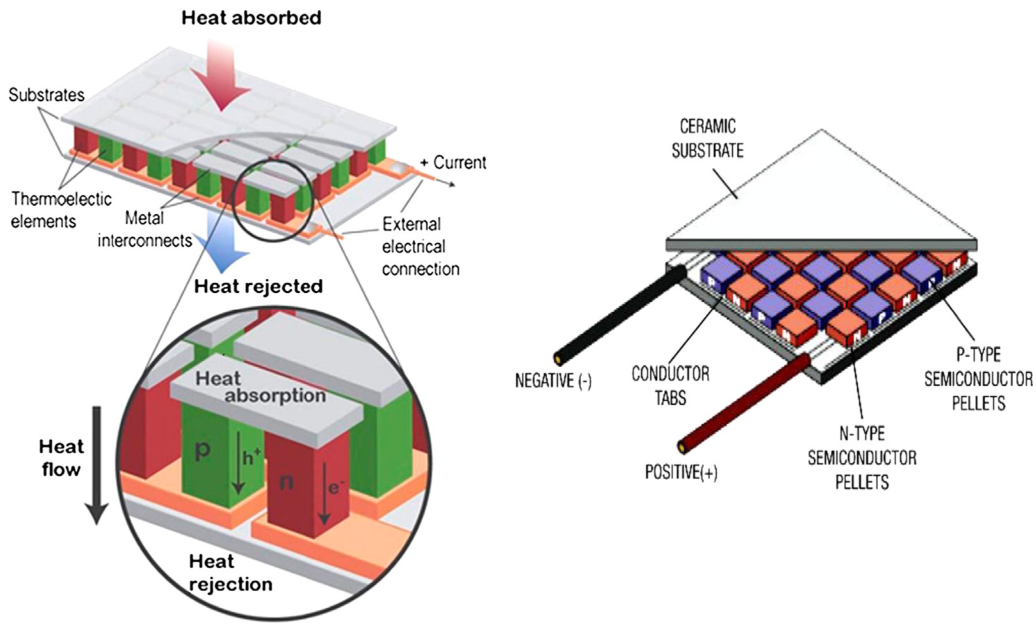

Fig. 1. Schematic view of p–n junctions in TEG devices [14,15].

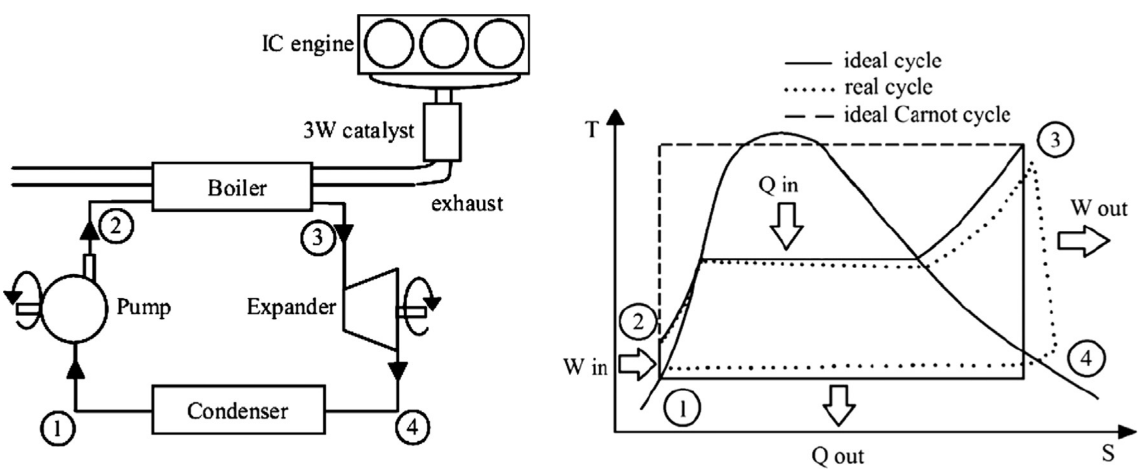

Fig. 2. Schematic of Organic Rankine Cycle (ORC) on diesel engine and T-S Diagram [19].

losses which is known as back pressure which reduces the engine's performance.

2.2. Organic Rankine Cycle

A number of thermodynamic cycles such as Calina, trilateral flash, Goswami and Rankine are presented in the literature for exhaust waste heat recovery from engines [14]. Among these cycles, Organic Rankine Cycle (ORC) can be introduced as the most efficient cycle for low temperature sources such as engine exhaust. A schematic of the ORC is shown in Fig. 2 which contains boiler, expander, condenser, pump and working fluid [19]. Many works are performed in this field and complete reviews of them are presented by Sprouse et al.[20],Chen et al. [21] and Wang et al. [22]. Most of these works are based on the effect of working fluid type on the ORC performance. The different types of working fluids are wet, dry and isentropic fluids with their T–S diagram slopes being positive, negative and infinite, respectively [14]. Chen et al. [21] by comparing 35 kinds of working fluids reached to the fact that suitable working fluid depends on the operating condition and a working fluid does not have maximum efficiency at all conditions. Dai et al. [23] mentioned that organic working fluids are more suitable for low temperature sources such as engine exhaust from the knowledge that wet fluids are never recommended for ORC due to the interaction between fluid particles and turbine blades.

2.3. Six stroke engines

The six-stroke engine is a type of internal combustion engine based on the four-stroke engine but with additional complexity intended to make it more efficient and reduce emissions. Three types of six-stroke engines have been developed since the 1890s [14], but in one of them proposed by Conklin and Szybist [24], the engine captures the heat lost from the four-stroke diesel engine and uses it to generate an additional power without more fuel consumption. A schematic of the operation of this engine is shown in Fig. 3. As seen, there are two power strokes: one with fuel, the other with water injection by using the waste heat of burned gases in the previous stroke. Water injection is occurred after compressing the burned gases from first stroke when the crank shaft angle is 720°. Mean effective pressure (MEP) of these engines will be increased by increasing the injected water amount. The main advantages of this engine is reducing the emissions and using

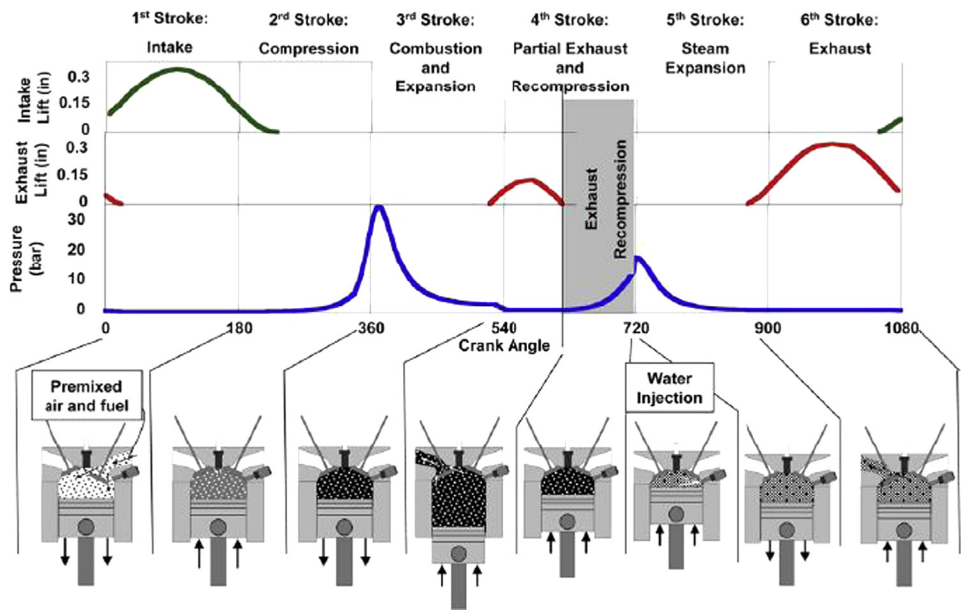

Fig. 3. Six stroke engine operation [24].

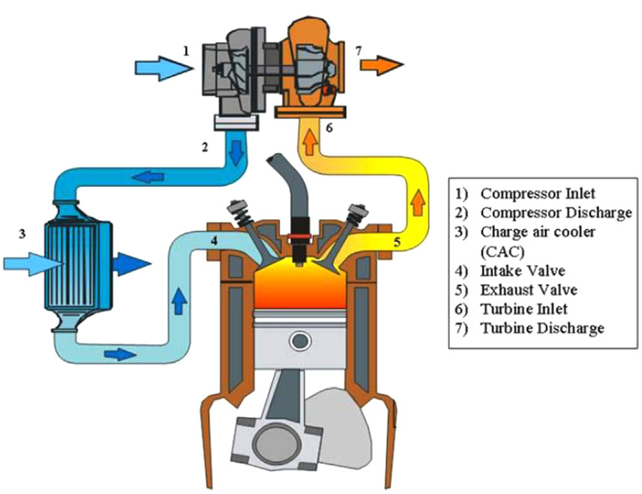

Fig. 4. Schematic view of turbocharging.

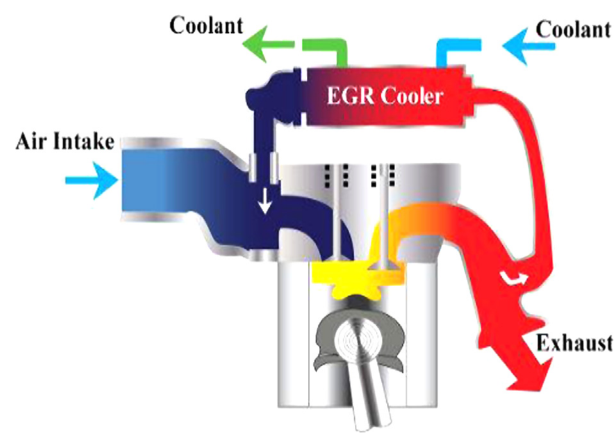

Fig. 5. EGR principle.

from two main waste heat sources because injected water can be preheated by using an exhaust heat exchanger which will completely be discussed in this paper.

2.4. Turbocharging

The first idea of turbochargers was proposed by Dr. Alferd J. Buchi in 1915 which he developed it on a diesel engine [14]. Actually, a turbocharger is a supercharger driven with exhaust gases energy and increases the engine power by compressing the inlet air to engine. Fig. 4 shows a turbocharger with its appurtenances. A turbocharged engine is more powerful and efficient than a naturally aspirated engine because the turbine forces more air and proportionately more fuel into the combustion chamber than atmospheric pressure alone, but it has some shortcomings. Turbo-lag i.e., (hesitation or transient response) during low speed acceleration and major concerns with heated bearings are two main shortcomings in turbochargers which are approximately solved by using two stages turbochargers [25] and variable geometry turbines (VGT) [26]. Another concern in turbochargers is increasing the intake air temperature due to its pressure increase. The warmer intake air has the less density and the less oxygen is available for the combustion event which reduces volumetric efficiency. Not only excessive intake-air temperature reduces efficiency, it also leads to engine knock or detonation known as a destructive factor in engines. So, turbocharger units often use an intercooler (also known as a charge air cooler) to cool down the intake air as shown in Fig. 4. Recently, a novel exhaust steam recovery called steam turbocharging is presented by Fu et al. [27]. They set a Rankine steam cycle system coupled on engine exhaust pipe which utilizes the exhaust energy of engine in order to generate steam and then drive the turbine. Their results show that IC engine power can theoretically be improved by 7.2% at most and thermal efficiencies can be raised up to 2 percent or more.

2.5. Exhaust gas recirculation

Recirculation of the exhaust gases into cylinder or EGR is one of the efficient methods to decrease the NOx level. EGR can be applied internally or externally in the engines. EGR is widely used in both gasoline and diesel engines reviewed by Wei et al. [28] and Zheng et al. [29], respectively. In a diesel engine, the exhaust gas replaces some of the excess oxygen in the pre-combustion mixture. Since NOx is formed primarily when a mixture of nitrogen and oxygen is injected into high temperature circumstances,

the lower temperatures of combustion chamber caused by EGR reduce the amount of the NOx. Although Ghazikhani et al. [6] mentioned that EGR cannot improve the combustion irreversibility, but it can be assumed as a technique for using the heat of burned gases in the cylinder for another time [30]. Furthermore in modern diesel engines, the EGR gases are cooled with a heat exchanger in order to enter a greater mass of recirculated gases (Fig. 5).

2.6. Engine heat exchangers

One of the most common ways to recover heat from engines is using the heat exchangers. Although heat exchangers are used in ORC cycles which were previously discussed in Section 2.2, they can separately be used for obtaining the heat from the exhaust for other applications such as hot water for domestic uses or utilizing as injection in cylinder, turbocharger, EGR, etc. Due to the high applications of heat exchangers, researchers have tried to improve heat transfer through special design of heat exchangers. Eventually, the main goal of present study is to review different types of heat exchangers modeled or tested in exhaust of engines. Although a few studies are performed in this field, but they can be developed and filled the gaps in this area. Review to these works and suggestions for future works is introduced in Section 4. Before that a short review of heat exchangers and the methods of heat transfer increasing are necessary which will be presented in the following section.

3. Heat exchangers (HEXs)

Heat exchangers (HEXs) are devices for efficient heat transfer from one medium to another. They are widely used in space heating, refrigeration, air conditioning, power plants, chemical plants, petrochemical plants, petroleum refineries, natural gas processing, sewage treatment, combustion engines, etc. [31]. A short review of HEXs types and the related methods for increasing the heat transfer are presented in the following.

3.1. Types of HEXs

HEXs can be classified according to various aspects. For instance, classifications of HEXs in accordance with their flow arrangement are parallel-flow, counter-flow and cross-flow. According to contact mechanism between hot and cold fluids is recuperative, regenerative and direct contact. Also, HEXs can be classified on the basis of their mechanism properties such as double pipe, shell and tube, spiral tube, gasket , spiral plate, lamella, finned plate and finally finned tube heat exchangers [31,32]. Due to the many various types of HEXs, selecting optimal heat exchangers is the main challenge. To select an appropriate heat exchanger design, the limitations of each model should be considered firstly. Though production cost is often the primary limitation, other aspects such as temperature ranges, pressure limits, thermal performance, pressure drop, fluid flow capacity, the ability of cleanness, maintenance, materials, etc. are also important and should be taken into account.

3.2. Heat transfer increasing methodologies in HEXs

Commonly, heat exchangers are designed to maximize the surface area of the wall between the two fluids while minimizing the resistance of fluid flow through the HEX for more efficiency. Some efficient techniques are available to increase the heat transfer rate in the HEXs which can be classified into two main groups, active and non-active methods. The difference between these two main groups is related to exerting external force to the HEXs. Using fins [33–35], coated surfaces [36], displaced insert devices, micro-channels [37], swirl flow devices [38], coiled tubes [39], nanoparticles additives [40,41], porous media [42–44], baffles and corrugated tubes [45], vortex generators [46–55] are examples of non-active methods which do not need t any external forces, while mixing and vibrating the fluids by a mechanical device or magnetic and electric fields (MHD [56–58] and EHD [59]), blowing injection or external fluid jet are samples of active methods which an external force is applied to HEX for increasing the heat transfer.

4. Engine HEXs

As described in Section 2.6, heat exchangers are widely used in the engines for heat recovery lonely or combined with other heat recovery technologies such as TEG, EGR, ORC, etc. which their applications are shown in Figs. 2, 4 and 5. Versus high applications of the HEX in engines and existence of many methods to increase the heat transfer in HEX, just limited cases are presented for using and improving the HEXs in engines. The afore-mentioned researches are introduced separately and compared in the following:.

4.1. HEXs in cylinder

Cylinder is the highest temperature source for heat recovery in engines. Although cylinders were commonly cooled by radiators, but Ghazikhani et al. [60] considered a separate circuit for cylinder cooling to reduce the brake specific fuel consumption (BSFC) in a two stroke SI engine (Fig. 6). They reported the effect of engine speed and torque on exergy balance and irreversibility. Their outcomes reveal that when torque or speed increases, the pressure and temperature in the cylinder will rise and makes an increase in exhaust gas availability and as a result the internal irreversibility decreases. So, more exergy will be recovered in higher load and speeds. They demonstrated thatdue to using this recovered exergy from water, BSFC will be reduced about 14.1% [60].

4.2. HEXs in radiator

Another main application of HEXs in engines is radiators constructed of a pair of header tanks, linked by a core with many narrow passageways, giving a high surface area relative to volume. Engines are often cooled by circulating a liquid called engine coolant through the engine block. Engine coolant is usually water-based, but may also be oil or nanofluid for increasing the heat transfer rate. Peyghambarzadeh et al. [61] prepared five different concentrations of water based nanofluids in the range of 0.1–1 vol% of Al_2O_3 nanoparticles for an engine radiator and found that nanofluids enhance heat transfer efficiency up to 45% in comparison with pure water [61]. The same practical experiment was done by Leong et al. [62]using copper nanoparticles in water and ethylene glycol which reported that about 3.8% of heat transfer enhancement could be achieved by adding2% copper particles into ethylene glycol at the Reynolds number of 6000 and 5000 for air and coolant, respectively [62]. A same research was performed by Ebrahimi et al. [63] using SiO_2 and found that using nanofluid as a coolant can improve the heat transfer rate and reduce the fuel consumption.

4.3. HEXs in exhaust

Some researchers attempt to enhance the rate of heat transfer by a special design of HEXs in the exhaust of diesel engines due to their high applications discussed in the previous sections. Zadsar and Gorji-Bandpy [38] used a twisted tape in the exhaust of an OM314 diesel engine in order to increase the recovered heat

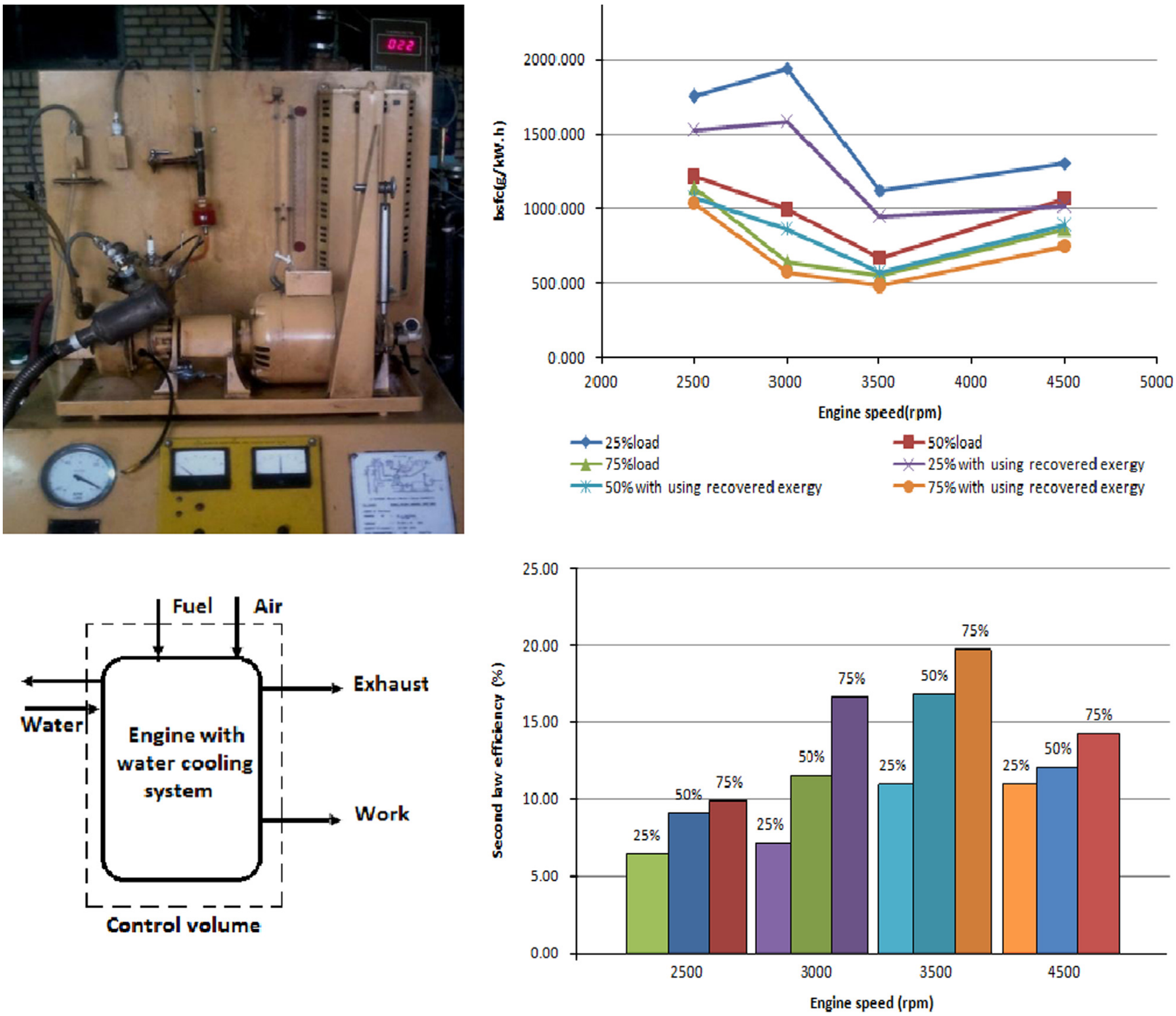

Fig. 6. Engine cylinder cooling, second law efficiency of heat recovery and BSFC reduction [60].

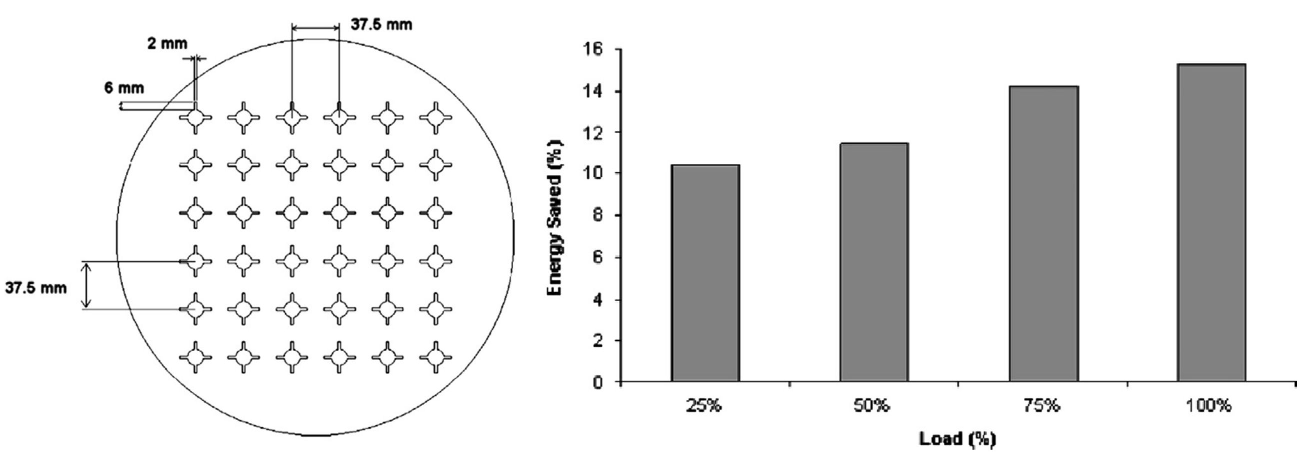

Fig. 7. Heat exchanger designed by [64] and heat recovery rate.

and their usage in a refrigeration cycle experimentally. Pandiyarajan et al. [64] designed a finned-tube heat exchanger as shown in Fig. 7. They used a thermal energy storage using cylindrical phase change material (PCM) capsules and found that nearly 10–15% of fuel power is stored as heat in thecombined storage system in different loads as seen in Fig. 7. Furthermore, Lee and Bae [65] made a little heat exchanger with fins in the exhaust by design of experiment (DOE) technique. They reported that fins should be in the exhaust gases passage for more heat transfer (Fig. 8) and designed 18 cases with different fin numbers and thicknesses and found the most

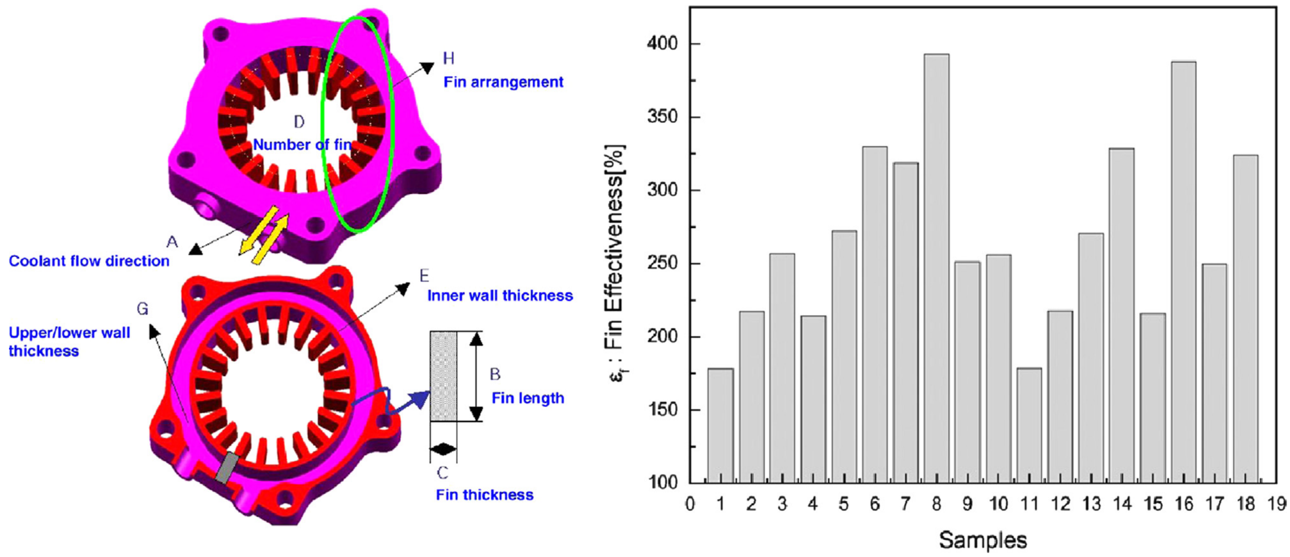

Fig. 8. Heat exchanger designed in [65].

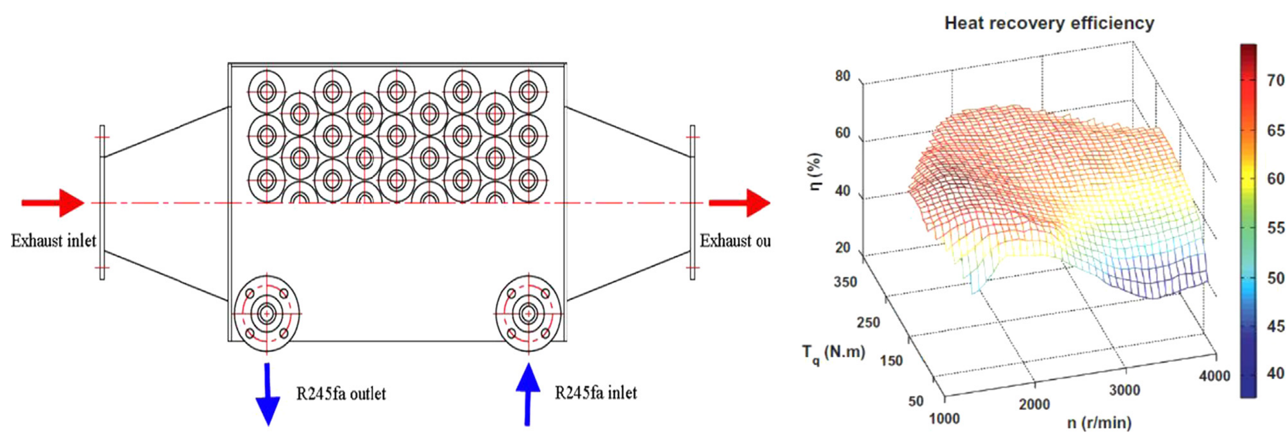

Fig. 9. Finned tube heat exchanger designed by Zhang et al. [66] for ORC application.

effective cases as shown in Fig. 8. Zhang et al. [66] modeled a finned tube evaporator heat exchanger for an ORC cycle as shown in Fig. 9. They concluded that waste-heat recovery efficiency is between 60% and 70% for most of the engine's operating region and also they mentioned that heat transfer area for a finned tube evaporator should be selected carefully based on the engine's most typical operating region. Ghazikhani et al. [67] used a simple double pipe heat exchanger in a diesel engine and performed an exergy analysis for finding the relation between irreversibility and exhaust sound level. Recently, they [68] estimated an experimental work that BSFC could be improved approximately up to 12% in different loads and speeds of an OM314 diesel engine by utilizing the recovered exergy from a simple double pipe heat exchanger in exhaust (Fig. 10). Also, they showed that exergy recovery will be enhanced by increasing the engine loads and speeds especially in high speeds.

As described in Section 2.1, using thermoelectric modules for heat recovery needs two heat sources, cold and hot. So, HEXs can be a suitable device for providing these sources which can simultaneously produce electricity and hot water. Weng and Huang [69] designed a heat exchanger with radial fins and TEG device as illustrated in Fig. 11 and studied the effect of HEX length and TEG number on heat recovery. They mentioned that the total generated power increases with rising the length of HEX l or enhancing the TEG number which gets saturated quickly. However, the average power per TEGs number has an opposite variation trend. This item is related to the fact that the total power generation is proportional to the total number of TEGs . It is necessary to mention that increasing the HEX length rises the TEG numbers but on the contrary reduces the amount of temperature difference [69]. Also, Lu et al. [70] designed a heat exchanger on exhaust automobile as Fig. 12 in different outlet and inlet pipe numbers and observed maximum 2.5 kPa pressure drop for that. Furthermore, Love et al. [71] used a HEX in exhaust of engine with TEGs for improving the TEGs performance as presented in Fig. 13 and observed that for higher exhaust gas flow rates, thermoelectric power output enhances from 2 to 3.8 while overall system efficiency declines from 0.95% to 0.6%.

Yang et al. [72] invent a heat pipe (a kind of heat exchanger) for cooling the exhaust of a large bus and modeled it numerically and finally obtained a good agreement between numerical and experimental outcomes. Although most of the studies in ORC use simple double pipe or shell and tube HEX [20–22], some of them introduced a special design for increasing heat transfer. For example,Wang et al. [73] suggested a heat exchanger as shown in Fig. 14, it seems that this kind of HEX has high back pressure, but in their study the total fuel saving of the engine reached up to 34% which is under some of the operating conditions. Recently, Hossain and Bari [74,75] applied a new HEX for a diesel engine presented in Fig. 15 experimentally and numerically. After that they optimized the working fluid pressure and the orientation of heat exchangers and found the additional power increased from 16% to 23.7%. Also, they investigated the parallel and series

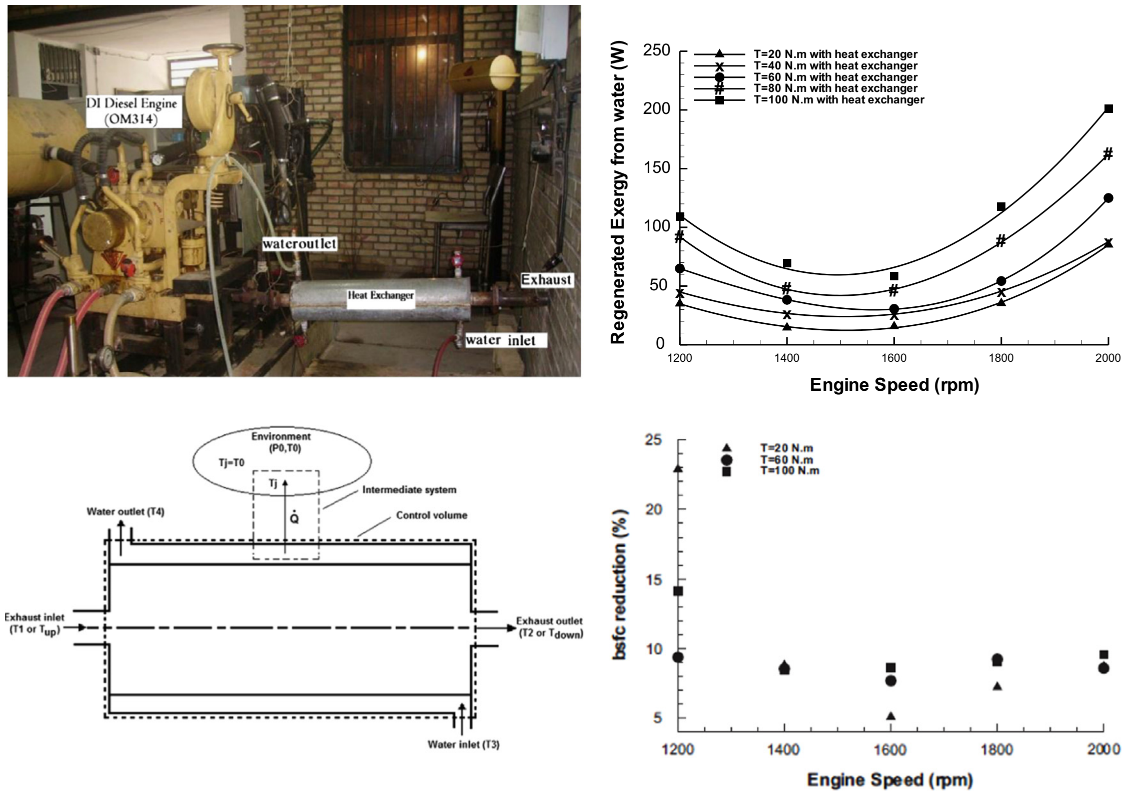

Fig. 10. Double pipe heat exchanger used in Ref. [68], exergy recovery and BSFC reduction.

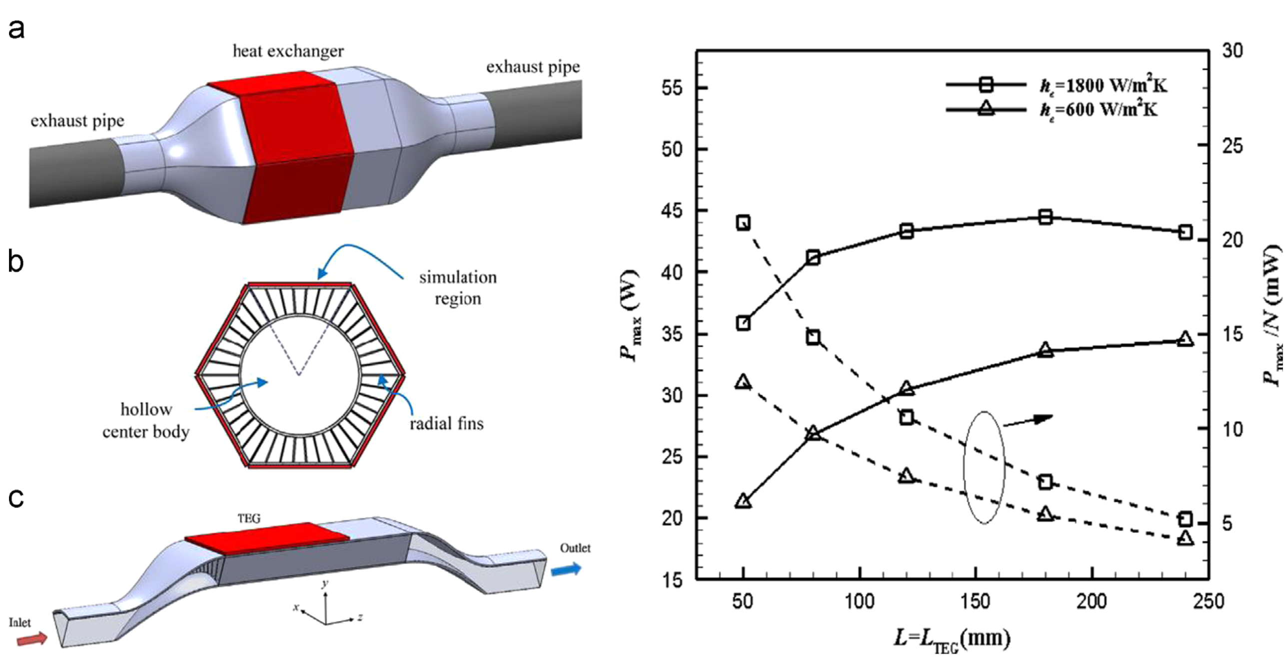

Fig. 11. Heat exchanger designed with thermoelectric and radial fins [69].

configurations of HEXs and as a result obtained additional power are shown in Fig. 15. To understand more, other experimental design of HEX for refrigeration cycle and thermoelectric installation has been presented in Refs [76,77] and [78,79], respectively. Mavridou et al. [80] examined two groups of configurations: (a) a classical shell with a tube heat exchanger using staggered cross-flow and (b) a cross-flow plate heat exchangerwhich is initially placedwith finned surfaces on the exhaust gas and then is covered with metal foam instead of the fins.They attempt to minimize the volume and weight of the arrangementand simultaneously keep the heat transfer from the gas side at a maximum range. Kauranen et al. [81] used phase change materials (PCM) and latent heat accumulator (LHA) for diesel exhaust waste heat recovery which help to decrease the fuel consumption and also its emission reduction. In a different study,Baker et al. [82] designed a multi-pass duct shape heat exchanger (Fig. 16) for a diesel engine by numerical finite difference method (FDM) and examined the effects of TEG, porous structure and fins for the amount of heat

recovery.Then, they found that 1.06 kW is the maximum net electrical powerwhich can beachieved for the three parallel flow paths in a counter-flow arrangement. Also, Deng et al. [79] designed two thermoelectric HEXs models shown in Fig. 17 by CFD simulation and used Wilcox k-ω model to discuss on different internal structures, lengths and materials on the HEX performance. The same study has been performed by Kumar et al. [83] which modeled three HEXs (rectangular, triangular and hexagonal) by CFD FLUENT software and experimentally produced and tested the best model.

For comparison the above schemes for exhaust HEXs, Table 1 is provided with additional information from the above works. This table contains authors' names, year of paper publication, methodology of their study, the type of engine and HEX and some main outcomes based on the cost of efficiency, BSFC, optimization and other parameters studied by them. Because in all these papers, the same and full data are not presented and on the other hand, they are done on different engine types with different displacement volumes, exhaust temperatures and mass flow rates, a comparative study for selecting the best HEX model is rather difficult. Anyway, as described above and seen in this Table, 12% improvement in fuel economy and 23.7% power improvement have been reported in experimental works in the highest level done by Ghazikhani et al. [68] and Bari and Hossain [75] while, these values are much greater in ORC modeling studies. It can be concluded from this Table that using fins is more appropriate than foams and porous materials due to lower pressure drop and higher heat transfer rate. Also, using the PCM as a heat storage source, lower TEGs in downstream of HEX, designing parallel HEXs or HEX with one inlet and two outlets, selecting the best solid material such as TEGs material and working fluid can help the exhaust heat recovery and reduce the amount of fuel consumption.

As seen, most of the fuel economy improvement has been reported in ORC modeling studies which Wang et al. [22] reviewed them and the less one is reported in special HEX design studies. For instance, Wang et al. [22] reported that the maximum of fuel economy improvement is about 32%in a special work condition. Also, Saidur et al. [14] pointed out that up to 4.7% improvement in fuel economy efficiency by TEG and 7% improvement by using ORC are reported by the researchers. In a thermo-economic study of different working fluids in ORC, Sprouse et al. [20] reported that n-butane is more economic fluid than other working fluids. Also, Hajabdollahi et al. [84] showed that in a thermo-economic study, the optimum result of R123 indicates 0.01%, 4.39%, and 4.49% improvement forthe total annual cost in comparison with R245fa, R22, and R134a, respectively. Recently, Will [85] proposed a novel waste heat recovery in diesel engine with an external engine oil bypass and found about 7% improvement in the fuel economy.

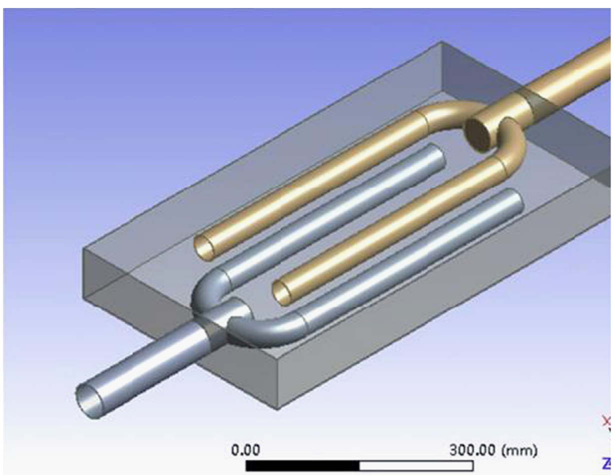

Fig. 12. TEG heat exchanger designed by Lu et al.[70].

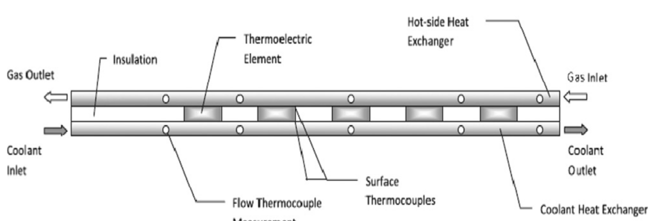

Fig. 13. Exhaust heat exchanger used by [71].

5. Exhaust HEX modeling and analysis

In this section, some necessary equations for modeling and analysis of the exhaust HEX are presented. Three dimensional, steady-state and turbulent flow are common assumptions for exhaust HEX modeling. When the problem assumed to be steady, the time dependent parameters will drop from the governing equations of the flow and conjugate heat transfer. The resulting equations are [75]:

Continuity equation:

$$\nabla.(\rho\vec{V})=0 \tag{1}$$

Momentum equations:
x - momentum:

$$\nabla.(\rho u\vec{V})=-\frac{\partial p}{\partial x}+\frac{\partial\tau_{xx}}{\partial x}+\frac{\partial\tau_{yx}}{\partial y}+\frac{\partial\tau_{zx}}{\partial z} \tag{2}$$

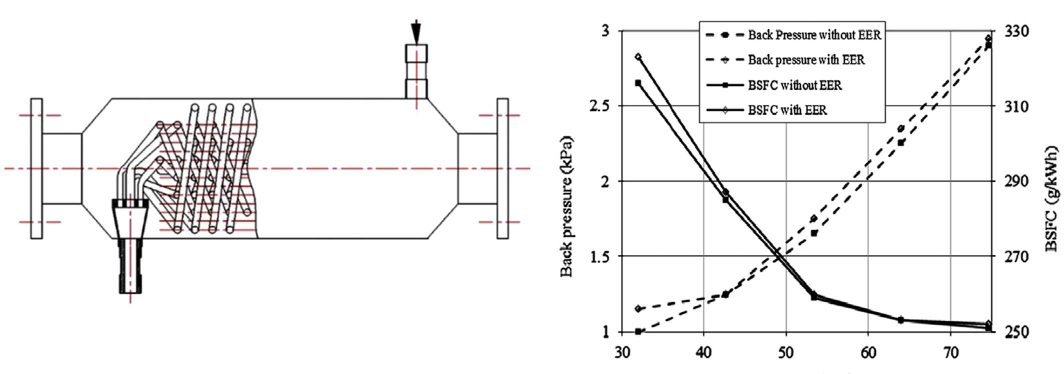

Fig. 14. Exhaust heat exchanger used in Love et al. [73] and its back pressure and BSFC.

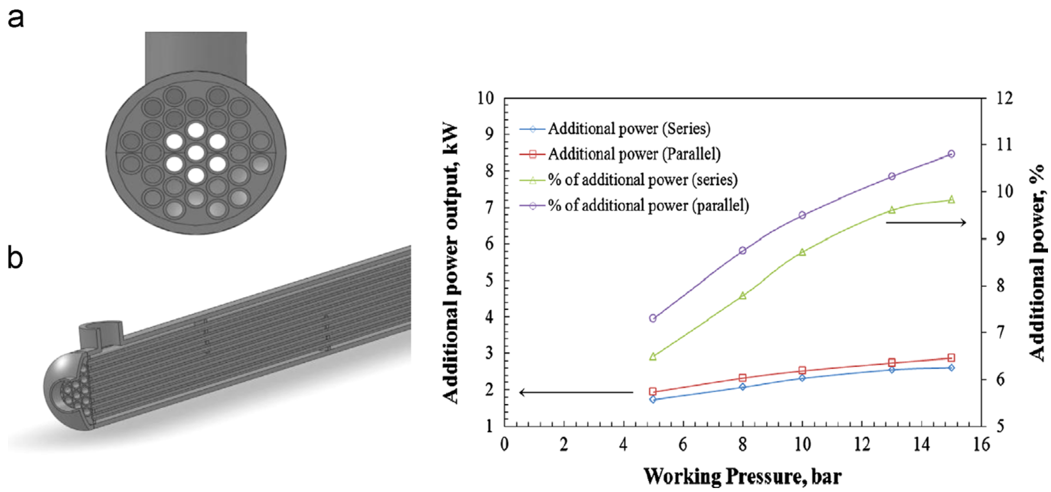

Fig. 15. Heat exchanger used by Hossain and Bari [74] and recovered power in parallel and series configurations.

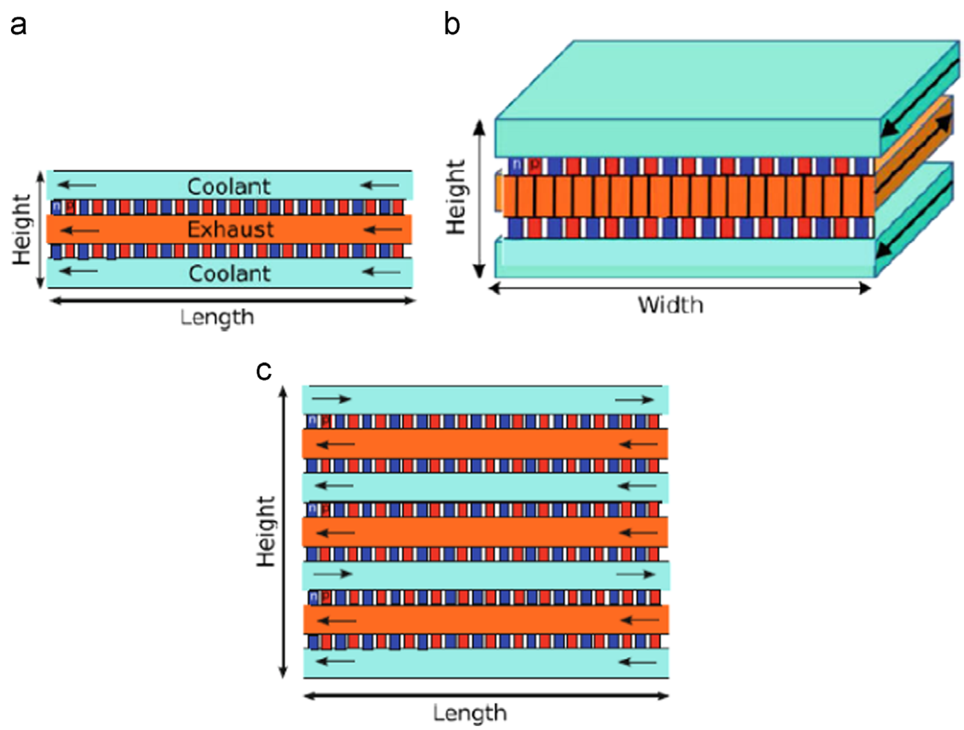

Fig. 16. Duct shaped HEX designed by Baker et al. [82] for studying the TEG, Fins and Porous structure effect on exhaust waste heat recovery (a) cross-section view (b) finned configuration and (c) multiple parallel duct counter-flow configuration.

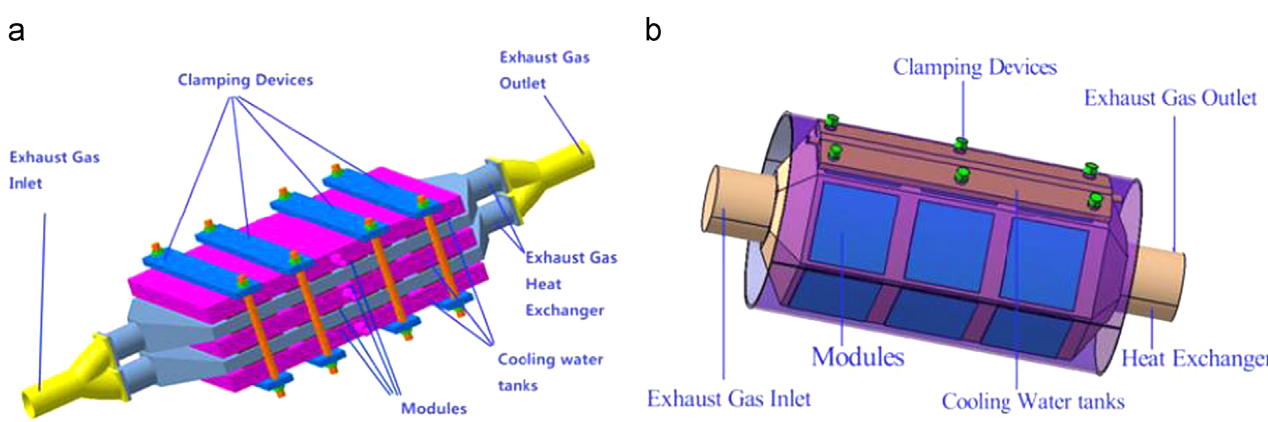

Fig. 17. Thermoelectric HEX designed by Deng et al. [79], (a) plate-shaped and (b) hexagonal-prism-shaped.heat exchanger.

Table 1
Comparison the results of different HEX designs by researchers in the literature.

Reference, year	Methodology	Enginetype	HEXtype	Mainoutcomes
Pandiyarajanetal. [64],**2011**	Experimental	Twin cylinder, four stroke diesel engine	Shell and finned tube HEX (Fig. 7)	• Nearly 10–15% of total heat is recovered. • The maximum heat extracted at full load condition is around 3.6 kW. • A cascaded latent heat storage system with multiple PCM is suggested for more heat recovery.
LeeandBae [65],**2008**	Experimental and Taguchi method	1.0 L SI engine	Small fin-tube HEX with circulating coolant (Fig. 8)	• Fin geometric parameters and the direction of the circulating coolant were the main affecting factors on the cooling performance. • The heat exchanger that had maximum effectiveness was not necessarily the optimum design.
Zhangetal. [66],**2013**	Mathematical ORC modeling	Four cylinder, R425 diesel engine	Finned tube HEX (Fig. 9)	• The overall heat transfer rate of the evaporator increases with engine power and reaches 70.4 kW at the rated power point. • The heat transfer area of the preheated zone is the largest, which is almost half of the total area.
Ghazikhanietal. [68],**2014**	Experimental and exergy analysis	Four cylinder OM314 diesel engine	Simple double pipe HEX (Fig. 10)	• 12% reduction in BSFC. • Second law efficiency of HEX is more related to engine speed than its torque.
WengandHuang [69],**2013**	CFD modeling, ANSYS-Fluent	Using data of previous works	Hexagonal HEX with radial fins and TEGs (Fig. 11)	• The heat sinks attached to the downstream TEGs possibly cause the downstream wall cooler. • Implementing more TE couples may not necessarily be worthwhile economically in the downstream. • The optimum length of the TEG cuboid is 80 mm for a heat exchanger of length 180 mm.
Luetal. [70],**2013**	Experimental	Used a heat source as automobile exhaust	Muffler-like HEX with different inlet and outlet numbers (Fig. 12)	• Design of 1-inlet and 2 outlet was more suitable than 2-inlet and 2 outlet due to higher heat transfer and lower pressure drop.
Love etal. [71],**2012**	Experimental	Single cylinder DI diesel engine	Longitudinal HEX with TEGs (Fig. 13)	• Stainless steel material has 30–40% lower heat recovery than aluminum material. • Efficiency can be improved by increasing the temperature and mass flow rate of exhaust gases.
Yangetal. [72], **2003**	Mathematical and experimental modeling	HS663, a large bus	Heat pipe HEX	• Experimental and numerical modeling are in good agreement. • The main benefit of heat pipe is low pressure drop (24.4 Pa) in normal work condition.
Wang et al. [73], **2013**	Experimental and ORC numerical simulation	Four cylinder CA4GA1 gasoline engine	Multi-coil helical HEX (Fig. 14)	• Flow rate of working fluid plays an important role in HEX efficiency. • Back pressure increased due to HEX geometry. • Total fuel saving was up to 34% under 2000 rpm and 75 Nm
Hossain and Bari [74], **2013**	Experimental and CFD modeling	Four stroke, four cylinder, HINO W04D diesel engine	Shell and tube heat exchanger (Fig. 15)	• Improving the effectiveness of HEX from 0.44 to 0.76 by optimization design. • Parallel arrangement for two HEXs has 10% more economically than series. • Maximum recovered additional power was 2.9 kW at 15 bar which indicated 12% improvement in BSFC.
Bari and Hossain [75], **2013**	Experimental and CFD modeling	Four cylinder, 13B Toyota diesel engine	Shell and tube heat exchanger	• An additional 23.7% power improvement achieved by using water as the working fluid. • The additional power generation decreased at part loads.
Wojciechowski et al. [78], **2010**	Experimental	Light-duty diesel engine and Fiat SI engine	TEG generator	• It was more favorable to use TEGs in SI engine than CI engine due to higher temperature and lower mass flow rate of exhaust gases.
Deng et al. [79], **2013**	Experimental and CFD modeling	Four cylinder diesel engine	Hexagonal-prism-shaped and plate-shaped heat exchanger (Fig. 17)	• A plate-shaped heat exchanger made of brass with fishbone-shaped internal structure and length of 600 mm achieved a relatively ideal thermal performance.
Mavridou et al. [80], **2010**	ORC modeling with previous experimental data	Truck diesel engine	Shell and tube (smooth and finned) Plate and fin HEX (plain fins and metal foam)	• The lowest pressure drop was achieved by the standard plate and fin arrangement but if size and weight was also taken into account. • Substituting the fins with metal foam leads to a 38% reduction in volume and weight but has more pressure drop. • Shell and tube HEX had maximum pressure drop among other designs.

Table 1 (*continued*)

Reference, year	Methodology	Enginetype	HEXtype	Mainoutcomes
Baker et al. [82], **2012**	Numerical Finite difference modeling (FDM)	Cummins 6.7 L diesel engine	Duct shape HEX with TEG and fins (Fig. 16)	• Three way parallel ducts have more recovered heat than single duct • 32 fins in the duct, increase net power from 320 W to 975 W • Ducts filled by porous structure increased heat recovery but caused unacceptably large pumping work requirement.
Kumar et al. [83], **2011**	Experimental and CFD simulation	Three cylinder, four stroke SI engine	Rectangular, triangular and hexagonal HEX with TEG	• Bismuth telluride introduced as an effective module due to low cost and low operating temperature range with a considerable efficiency. • By considering cost, space, weight and performance, rectangular is chosen as the best HEX model.

y – momentum:

$$\nabla.(\rho\upsilon\vec{V}) = -\frac{\partial p}{\partial y}+\frac{\partial\tau_{xy}}{\partial x}+\frac{\partial\tau_{yy}}{\partial y}+\frac{\partial\tau_{zy}}{\partial z}+\rho g \tag{3}$$

z – momentum:

$$\nabla.(\rho w\vec{V}) = -\frac{\partial p}{\partial z}+\frac{\partial\tau_{xz}}{\partial x}+\frac{\partial\tau_{yz}}{\partial y}+\frac{\partial\tau_{zz}}{\partial z} \tag{4}$$

Energy equation:

$$\rho c_p\left(u\frac{\partial T}{\partial x}+\upsilon\frac{\partial T}{\partial y}+w\frac{\partial T}{\partial z}\right) = \lambda\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}+\frac{\partial^2 T}{\partial z^2}\right) \tag{5}$$

Commonly, the above equations are solved for HEX modeling by commercial CFD codes such as ANSYS, FLUENT, OpenFOAM, etc. which the HEX geometry is meshed in CFX, GAMBIT, etc. according to the literature, Renormalization-group (RNG) k–ε model and Shear-Stress Transport (SST) k–ω model are two suitable viscous models for simulating these kind of problems [69,74,75,79,83,86]. The amount of transferred heat or heat flux is an important parameter in HEX analysis. The average heat flux is [40] presented as follows:

$$\dot{Q}_{ave} = \frac{(\dot{Q}_g+\dot{Q}_c)}{2} \tag{6}$$

where Q_c is the heat transferred to the coolant which is calculated as:

$$\dot{Q}_c = \dot{m}_c C_{pc}(T_{c,out}-T_{c,in}) \tag{7}$$

In Eq.(7),$\dot{m}_c$is the mass flow rate of coolant and $C_{pc}$is the specific heat of coolant. Q_g is the heat transferred to the exhaust gases which for temperature-dependent specific heat can be calculated as:

$$\dot{Q}_g = \dot{m}_g\int_{T_{g,in}}^{T_{g,out}} C_{pg}\,dT \tag{8}$$

In the above equation,$\dot{m}_g$is the exhaust gases mass flow rate which is the sum of the intake air and fuel consumption mass flow rates [65]. By calculating Q_{ave}, the overall heat transfer coefficient, U(W/m K) for the HEX can be expressed as:[66]

$$U = \frac{\dot{Q}_{ave}}{L\Delta T_{LMTD}} \tag{9}$$

Where L is the axial length of HEX and ΔT_{LMTD} is the logarithmic mean temperature difference given by:

$$\Delta T_{LMTD} = \frac{\Delta T_{hot\ end}-\Delta T_{cold\ end}}{\ln(ET_{hot\ end}/\Delta T_{cold\ end})} \tag{10}$$

And ΔTs are

$$\Delta T_{hot\ end} = T_{g,in}-T_{c,out} \tag{11}$$

$$\Delta T_{cold\ end} = T_{g,out}-T_{c,in} \tag{12}$$

An important parameter calculated in the previous works for HEX analysis is HEX effectiveness. Effectiveness can be defined as the ratio of the actual heat transfer in a given HEX to the maximum possible rate of heat transfer, i.e. [74]

$$\varepsilon = \frac{(\dot{m}C_p)_g(T_{c,out}-T_{c,in})}{(\dot{m}C_p)_{\min}(T_{g,in}-T_{c,in})} \tag{13}$$

In order to estimate the energy availability of the HEX in exhaust, some researchers carried out the exergy analysis [74,68]. By considering some assumptions for simplification of the combustion product as ideal gas, the specific exergy of the exhaust is calculated by using the following equation [74]:

$$e = u-u_0+p_0(\nu-\nu_0)-T_0(s-s_0) \tag{14}$$

where

$$p_0(\nu-\nu_0) = \frac{\overline{R}}{M}\left(\frac{p_0 T}{p}-T_0\right) \tag{15}$$

And

$$(s-s_0) = s^0(T)-s^0(T_0)-\frac{\overline{R}}{M}\ln\frac{p}{p_0} \tag{16}$$

In the afore-mentioned equations, zero subscripts (0) denote dead states. Also, calculating the exergy destruction and irreversibility in the exhaust HEX are important parameters which can be found in [68]. The second law of efficiency for an exhaust HEX is defined as [68]:

$$\eta = \frac{\dot{m}_c(e_{c,out}-e_{c,in})}{\dot{m}_g(e_{g,in}-e_{g,out})} \tag{17}$$

Another important parameter used in diesel waste heat recovery analysis is BSFC. BSFC and can be calculated as follows:

$$BSFC = \frac{\dot{m}_f}{P_b} \tag{18}$$

where $\dot{m}_f$is the fuel mass flow rate and P_b is the brake power of diesel engine.

6. Conclusion

In this paper, a short review of heat recovery technologies in engines and heat exchangers has been presented. It seems that in most of these technologies (ORC, TEG, EGR, HEXs and turbo-charging), heat exchangers have an important role to transfer heat for recovering process, so a suitable design for heat exchanger should be applied in accordance with this fact that heat transfer increases when pressure drop is in the allowable limit. Some experimental and numerical researches about various heat exchangers designs existed in the literature which all of them

have been reviewed here. It can be concluded that using fins is more applicable and appropriate than foams and porous materials due to the lower pressure drop and higher heat transfer rate. Also, it seems that other methods for increasing the heat transfer such as vortex generators, nanofluids, using the PCM as heat storage source, etc., in addition to lower TEGs in downstream of HEX, design parallel HEXs or HEX with one inlet and two outlets, selecting the best solid materials, TEGs material and working fluids can enhance the exhaust heat recovery and save the fuel costs for future works.6

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